The Relative Roles of Soil, Land Cover, and Precipitation Uncertainty for Watershed-scale Soil Moisture Prediction in a Semi-Arid Environment

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ARMS Project Overview

Routine or operational estimates of hillslope-to-watershed scale soil moisture have potential applications in regional resource management, including flood and water resource forecasting, irrigation scheduling and determining mobility with lightweight vehicles. Hillslope scales may be defined as 10 to 100 m and watershed scales range from 1,000 to 25,000 km^2. Watershed management applications generally require daily soil moisture information to depths ranging from the sub-surface (~15 cm) to the entire root zone (> 1 m), while remote sensing-based products provide only surface soil moisture at depths ranging from 1-5 cm over typical bi-weekly to monthly intervals. Therefore, a combined approach using a Soil-Vegetation-Atmosphere-Transfer (SVAT) model (such as an LSM) and remotely sensed observations is developed to provide routine hourly-to-daily estimates of surface and profile soil moisture.

In this work, soil moisture was evaluated at the watershed scale using the community NOAH LSM (see Chen et al. 1996) as included in the Land Information System (LIS) framework (Kumar et al. 2005). The NOAH-LIS system was tested using soil moisture data from the Monsoon '90 experiment, carried out at the Walnut Gulch Experimental Watershed (WGEW) over an 18-day period during July and August 1990. The primary evaluation criterion was surface soil moisture retrieved from the NASA PushBroom Microwave Radiometer (PBMR). The effect of using global-to-continental scale boundary-condition information for soil and vegetation properties was evaluated in the system against more fine-scale property information for the watershed, which is not typically available. Also, the effect of using forcing precipitation from a high-density rain gauge network in the watershed was evaluated against precipitation from a single gauge in the watershed, from a mean of the gauge network, and from a global-to-continental scale reanalysis.

This work was performed as part of the **Army Remote Moisture System (ARMS)**. The goal of this applied research effort is to provide the U.S. Army with a prototype operational soil moisture modeling system based on remote sensing technology, process-based models, and geographic information (GIS) systems. This work encompasses estimates of soil texture as well as soil moisture through automated instrumentation, model inversion, and heuristic classification.

Soil Property Information

FAO, STATSGO, and SSURGO soil texture maps for the Walnut Gulch watershed are depicted in Figure 1. Only one soil texture type is found in the entire watershed for both FAO (sandy loam) and STATSGO (loamy sand), whereas the SSURGO map contains a mixture of types, generally sandy loam and sandy clay loam. The soil texture data was mapped to the texture classes of Cosby et al. (1984), which is the lookup table that NOAH uses to determine its soil hydraulic properties. Saturated hydraulic conductivity and porosity maps were also derived directly from the SSURGO data as an optional input to NOAH.

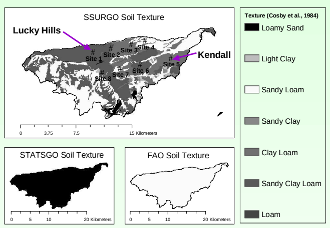

Figure 1: Soil texture maps at Walnut Gulch.

Precipitation Forcing

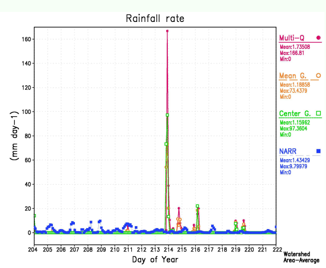

Figure 3: Watershed area-average forcing precipitation.

Vegetation Property Information

Three land cover datasets, at varying degrees of detail, were also used in this study: the 1992 NALC land cover dataset, the EPA/USGS land cover dataset, and land cover retrieved from the MODIS instrument. The datasets were mapped to the Dorman and Sellers (1989) 13-type land cover classification, in order to use the NOAH vegetation parameter lookup tables. The maps for Walnut Gulch are depicted in Figure 2. In all three datasets, the dominant type is open shrubland (shrubs with bare soil patches), although the NALC dataset does have a notable portion of ground cover (grasses). LAI, greenness, and albedo from Houser (1996) were also obtained as optional input to NOAH.

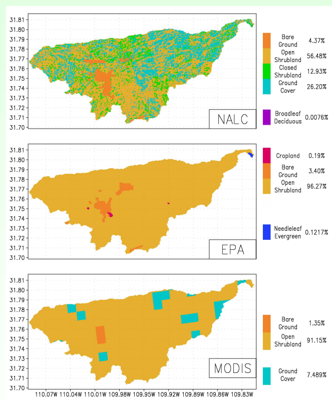

Figure 2: Vegetation land cover maps at Walnut Gulch.

The time series of the watershed area-average forcing precipitation from four different sources are depicted in Figure 3. The red curve is the average of the interpolated field (Garcia et al., 2006) from 84 rain gauges at Walnut Gulch. The orange curve is the mean of the 84 gauges and the green curve is a single gauge near the center of the watershed. The blue curve is from the NARR reanalysis at 0.33 degrees. The latter three experiments use the same precipitation value at each grid point, varying by timestep.

Model Description and Experimental Design

The community NOAH land surface model is a stand-alone, uncoupled, 1-D column model freely available at the National Centers for Environmental Prediction (NCEP). The name is an acronym representing the various developers of the model (N: NCEP; O: Oregon State University, Dept. of Atmospheric Sciences; A: Air Force (both AFWA and AFRL - formerly AFGL, PL); and H: Hydrologic Research Lab/NWS (now Office of Hydrologic Development, OHD). NOAH simulates soil moisture (liquid and frozen), soil temperature, skin temperature, snowpack depth, snowpack water equivalent, canopy water content, and the energy flux and water flux terms of the surface energy water balance.

The LIS system was configured to simulate over a 660 by 333 grid domain with a 40-meter horizontal grid spacing. A mask was created around the Walnut Gulch watershed within this domain, leaving 91960 tiles within the watershed. The simulations were initialized at 0000 local time on 23 Jul 1990 (Day Of Year = 204) and continued until 0000 local time on 10 Aug 1990 (DOY 222) using a 1200-second timestep. The initial soil moisture profile was a blend of in situ TDR observations from the Lucky Hills and Kendall Metflux sites. The initial soil temperature(s) was 293.0K, the bottom soil temperature was set to 286.5K, and no water was initially present on the vegetation. The NOAH model was configured with 10 vertical layers of soil moisture and temperature, with thicknesses of 5, 5, 5, 5, 10, 20, 20, 40, 60, & 80cm to a depth of 2.5 meters. Some NOAH simulations with changes to the soil properties, particularly to K_{sat}, required a much smaller timestep for stability with these relatively thin soil layers.

The base soil and vegetation parameters were meant to represent the real-world "worst-case" scenario of using any available data at a given watershed. These simulations represent the "control" runs and the effect of improvement to the boundary conditions datasets was tested. The base soils information is using the FAO soil type dataset to determine all soil properties. The base vegetation information is using the MODIS land cover dataset with albedo and greenness from the default NOAH climatology in the region. The base simulations, however, all used the 84-gauge interpolated precipitation, which is not typically available, in order to best test the effects of varying soil and vegetation information. The effects of varying precipitation information were separately tested using the base soils and vegetation information. The experimental design is as follows:

Soil Uncertainty (with interpolated 84 rain gauges): FAO soil type; STATSGO soil type; SSURGO soil types (all with soil parameter lookup table); SSURGO soil types with SSURGO K_{sat} and porosity; SSURGO soil types with SSURGO porosity; SSURGO soil types with SSURGO K_{sat}.

Land Cover Uncertainty (with interpolated 84 rain gauges): MODIS vegetation types; EPA vegetation types; NALC vegetation types (all with greenness and albedo climatology); NALC types with greenness and albedo maps; NALC types with albedo; NALC types with greenness.

Precipitation Uncertainty (with FAO soils and MODIS land cover): 84 rain gauges with multi-quadric interpolation; 84-gauge time-series mean at all grid points; Center gauge time-series value at all grid points; NARR precipitation.

Comparison to in situ data & PBMR at Metflux sites

NOAH model outputs as compared to the PBMR data and in situ gravimetric measurements at the Kendall Metflux site (Site #5 in Figure 1) are depicted in Figure 4. The left figure shows the effect of varying the soils information. The model and observations are both dry before the intense precipitation event late on 1 Aug (DOY 213). After the event, the model is wetter than the observations, with the observations drying out more rapidly than the model does, despite the range of soil property information. When varying the vegetation information, little effect was found, with the exception of increasing the greenness at this site, which caused the transpiration to increase as the expense of the bare soil evaporation, resulting in wetter surface soil moisture. Varying the forcing precipitation had a large effect (as expected), mainly as a result of the mean and center gauge forcings having lower overall magnitude of precipitation. The NARR analysis, over a wider area with lighter but more constant amounts, was too wet at first, but too dry after the observed intense precipitation event. Similar results were found at all 8 of the Metflux locations.

Comparison between Metflux observations and NOAH simulated fluxes are shown in Table 1. Despite the large range in simulated values, the model consistently produced too little latent heat flux and too much sensible heat flux at these sites. The large range from vegetation uncertainty mostly resulted in changes to transpiration without significantly affecting the surface soil moisture.

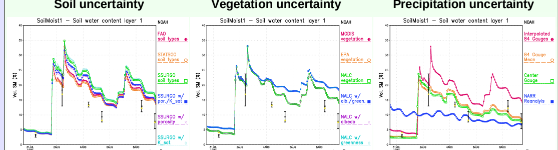

Figure 4: Surface volumetric soil moisture (VSM) time series at Kendall from the PBMR retrievals (yellow) and in situ gravimetric (black square with error bars) compared to NOAH model output.

Table 1: Daytime average latent & sensible heat fluxes at 8 Metflux sites with range of uncertainty experiments.

Variable	Observations	Soils	Vegetation	Precipitation
Qle (W m^{-2})	161.0	72.0 – 84.6	68.2 – 112.4	60.0 – 88.3
Qh (W m^{-2})	96.2	157.8 – 176.8	149.3 – 179.1	153.5 – 187.2

Comparison to PBMR Retrievals

Some representative comparisons between the NOAH simulated surface volumetric soil moisture (VSM) and the PBMR retrievals on various dates are shown in Figure 5. The left figure shows the effect of using the SSURGO soils data on the variation of the simulated moisture, two days after the intense precipitation event. The PBMR retrieval at this time shows some of this variation, but the model is too wet in some areas and has an overall wet bias. The center figure is using FAO soils data, and the simulated VSM is mainly reflecting the interpolated precipitation field near the end of the simulation. The model continues to be too wet at the surface, despite using the best available NALC vegetation data. The right figure uses the NARR precipitation at all grid points and the simulated VSM field is smooth. This PBMR image was taken right after the intense rain event which the NARR forcing does not capture; thus the model has a dry bias, especially in the wet area in the eastern portion of the PBMR retrieval. Similar plots were generated for all cases and times, and the bias and RMS errors are plotted in Figure 6. The SSURGO soils data with SSURGO K_{sat} and porosity did the best at reducing the wet bias in the model. Varying the vegetation data again had little effect on the surface VSM. When varying the precipitation forcing, using the mean of the gauges or the center gauge also reduces the wet model bias as a result of less precipitation in those forcings. The NARR precipitation was too wet early in the simulation, but too dry after the observed rain event in the watershed. All simulations shown so far used a NOAH transpiration factor of 1.0; the default value in NOAH is 2.0, which is shown to not be realistic in a semi-arid region in the right most figure. Reducing the transpiration leads to more bare soil evaporation and drier surface soil moisture.

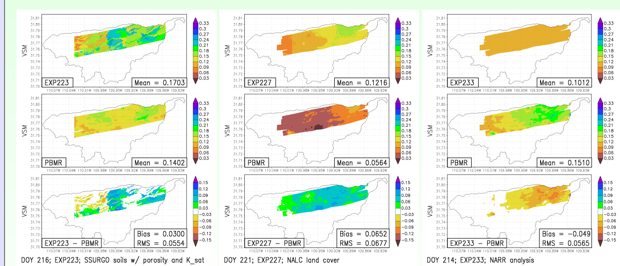

Figure 5: NOAH simulated (top), PBMR retrieved (middle), and difference of (bottom) surface volumetric soil moisture (VSM) during Monsoon '90 for SSURGO soil types with SSURGO K_{sat} and porosity (left) for DOY216, NALC vegetation types (center) for DOY221, and NARR precipitation (right) for DOY214.

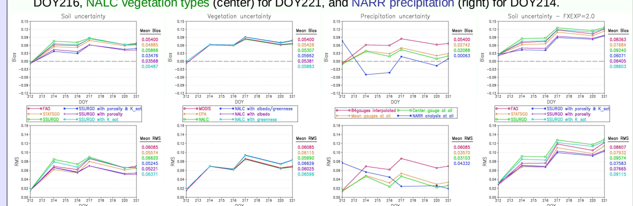

Figure 6: Bias (top) and RMS error (bottom) of NOAH simulated surface soil moisture (VSM) compared to 6 PBMR retrievals for soil (left), vegetation (2nd from left), and precipitation uncertainty (3rd from left) experiments. The figure on the far right shows the soil uncertainty with typical NOAH evaporation factor of 2.0 (instead of 1.0).

Summary

The NOAH model was evaluated over the watershed scale in a semi-arid region as compared to surface soil moisture and flux observations. For Monsoon '90, the model was shown to be too wet; particularly, it was unable to evaporate or drain the surface soil moisture as rapidly as observed. Also, the model produced more sensible heat and less latent heat than measured. These results were found despite a variety of soils and vegetation boundary condition datasets or precipitation forcings tested, which may point to some NOAH structural issues in physics of semi-arid regions. However, parameter estimation over this period has shown the ability of NOAH to more realistically simulate the surface soil moisture with calibrated soil parameters (Santanello, et al., 2006). These results will tested against simulations within other watersheds with different climatologies, such as Little River GA, Little Washita OK, and North Park CO.

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